Optical Time-Transfer for Bistatic SAR Small Spacecraft

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Outline

- Mission Concept
- Noise Sources and Clock Models
- Timing and Ranging Simulation
- Radar Simulation
- Summary and Conclusion

Mission Concept

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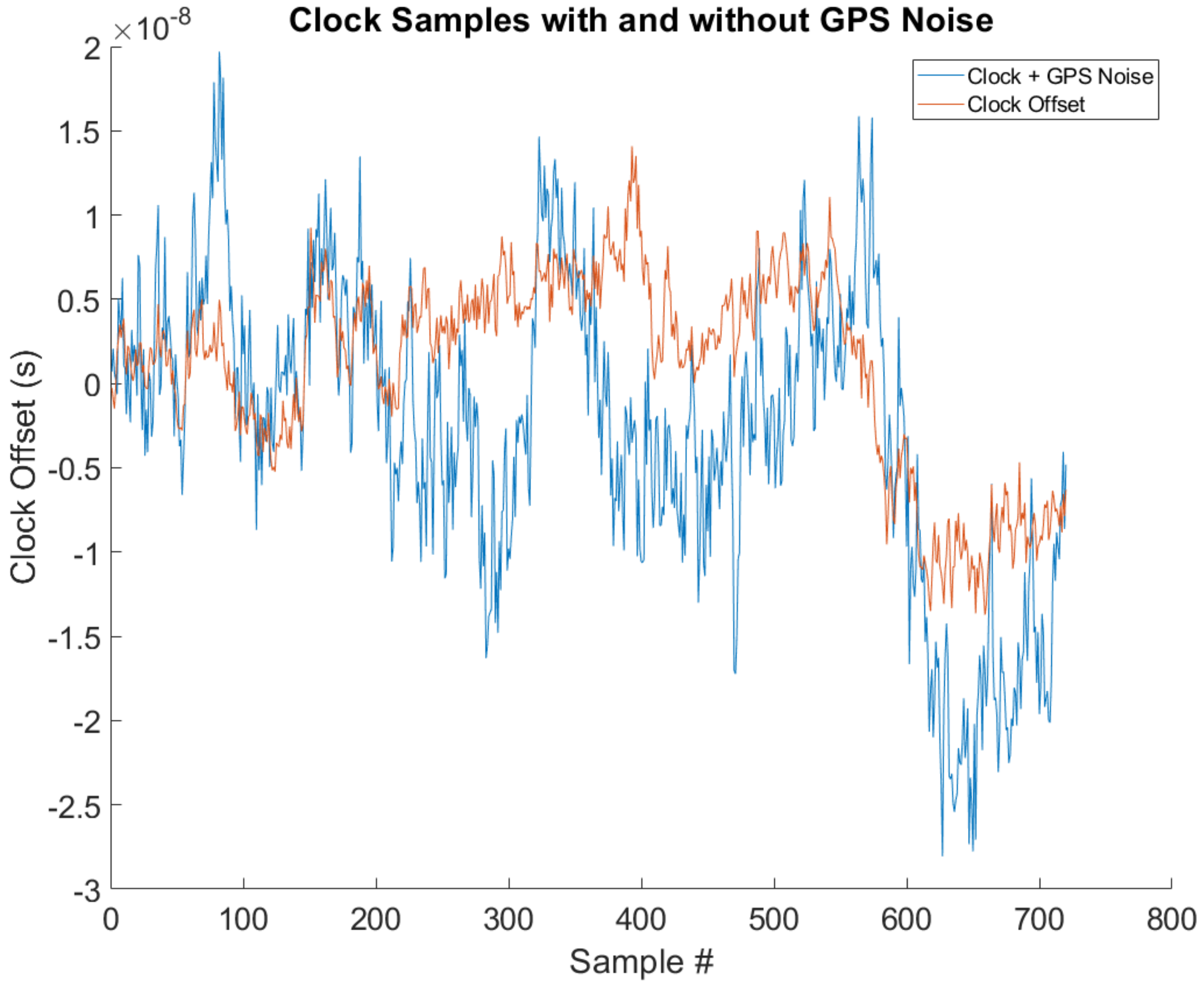
- CubeSat bistatic SAR in LEO
- Laser time-transfer clock synchronization
- Laser Time-Transfer Missions: T2-L2 (2008), CHOMPTT (2018), CLICK (exp. 2021)
- SAR Missions: TanDEM-X (2010), LuTan-1 (2020)

Parameter	Value
Orbit Altitude	500 km
Orbit Eccentricity	0
Spacecraft Line-of-Sight Distance	250 km
GPS Measurement Frequency	0.0083 Hz
Laser Pulse Transmission Rate	5 Hz

1. **T2-L2:** Exertier, P., et al. "Status of the T2L2/Jason2 Experiment", *Advances in Space Research*, Volume 46, Issue 12. 2010.
2. **CHOMPTT:** Conklin, J., et al., "Preliminary Results from the CHOMPTT Laser Time-Transfer Mission", Small Satellite Conference. Logan, UT. 2019.
3. **CLICK:** Serra, P., et al. "Optical Communications Crosslink Payload Prototype Development for the Cubesat Laser Infrared CrosslinK (CLICK) Mission", Small Satellite Conference. Logan, UT. 2019.
4. **TanDEM-X:** G. Krieger et al., "TanDEM-X: A Satellite Formation for High-Resolution SAR Interferometry," in *IEEE Transactions on Geoscience and Remote Sensing*, vol. 45, no. 11, pp. 3317-3341, Nov. 2007.
5. **LuTan-1:** Jiao, Y., Liang, D., Liu, K., Chen, Y., Wang, H. and Wang, R., 2020. The Synchronization Transceiver Design and Experimental Verification for the LuTan-1 SAR Satellite. *Sensors*, 20(5), p.1463.

Noise Sources

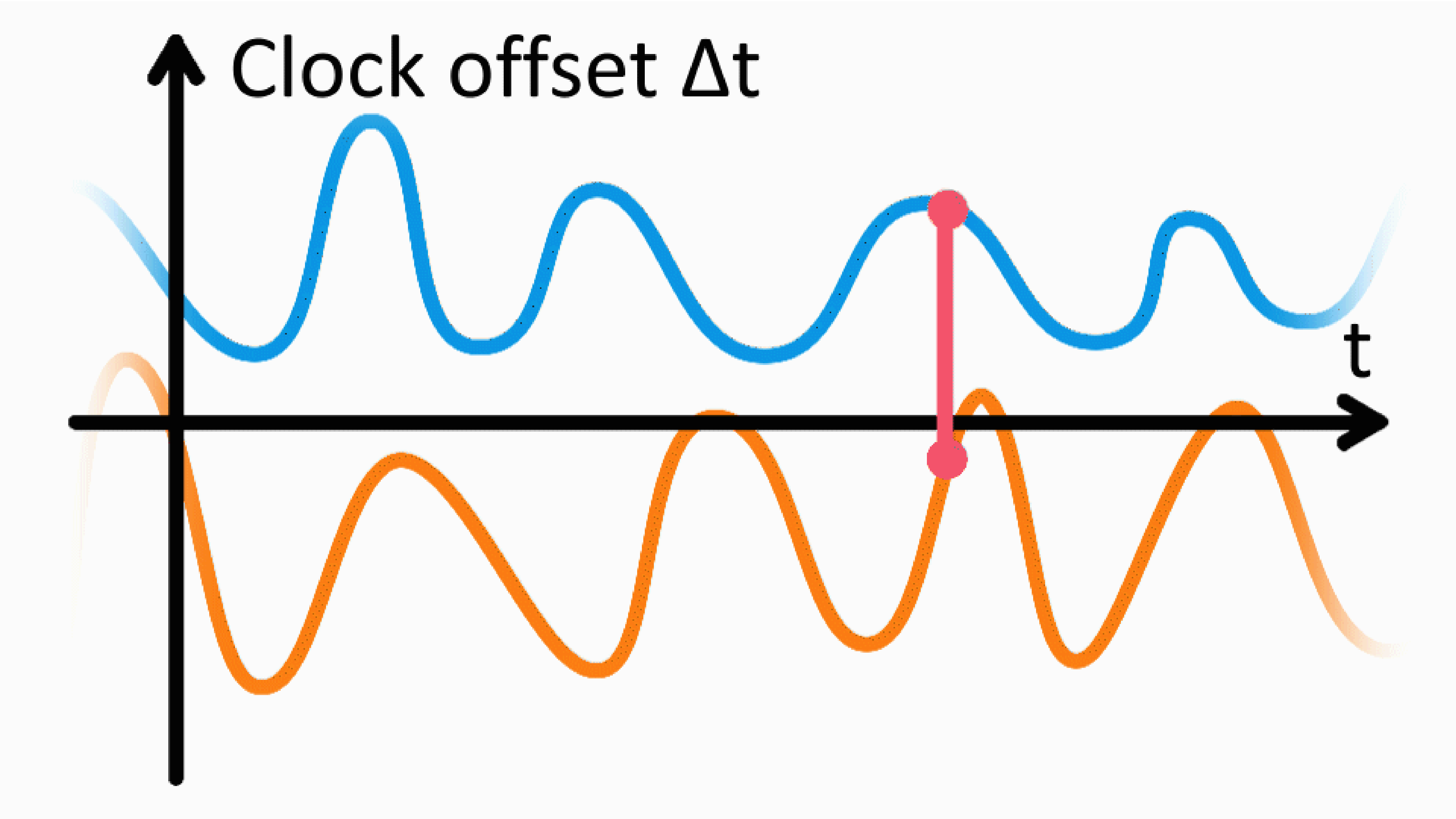
- Clocks: Non-Gaussian
  - GPS Timing Measurement
  - CSAC (Chip-Scale Atomic Clock)
  - MAC (Miniature Atomic Clock)
- Pulse detection noise: Gaussian
  - σ = 100 ps
- GPS position error: σ = 7 m



6. MAC and CSAC manufactured by Microsemi Corporation.

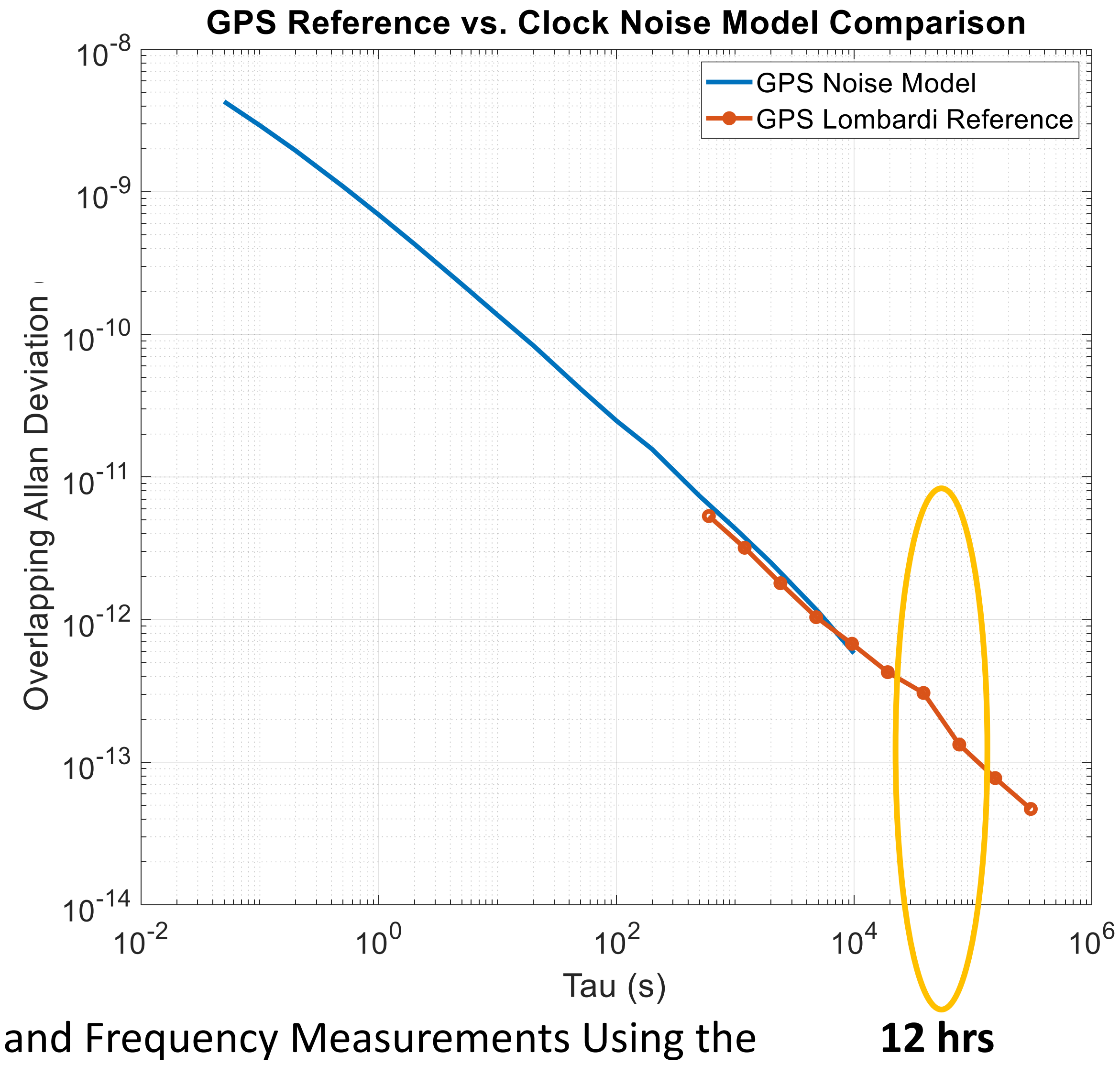
7. Pulse detection noise: Anderson, J., et al., "Sub-nanosecond ground-to-space clock synchronization for nanosatellites using pulsed optical links", *Advances in Space Research*, Volume 62, Issue 12. 2018.

8. GPS position error: Montenbruck, O., and Gill, E., *Satellite Orbits: Models, Methods and Applications*, Springer Berlin/Heidelberg. 2011.


Clock offset Δt
t

GPS Clock Noise

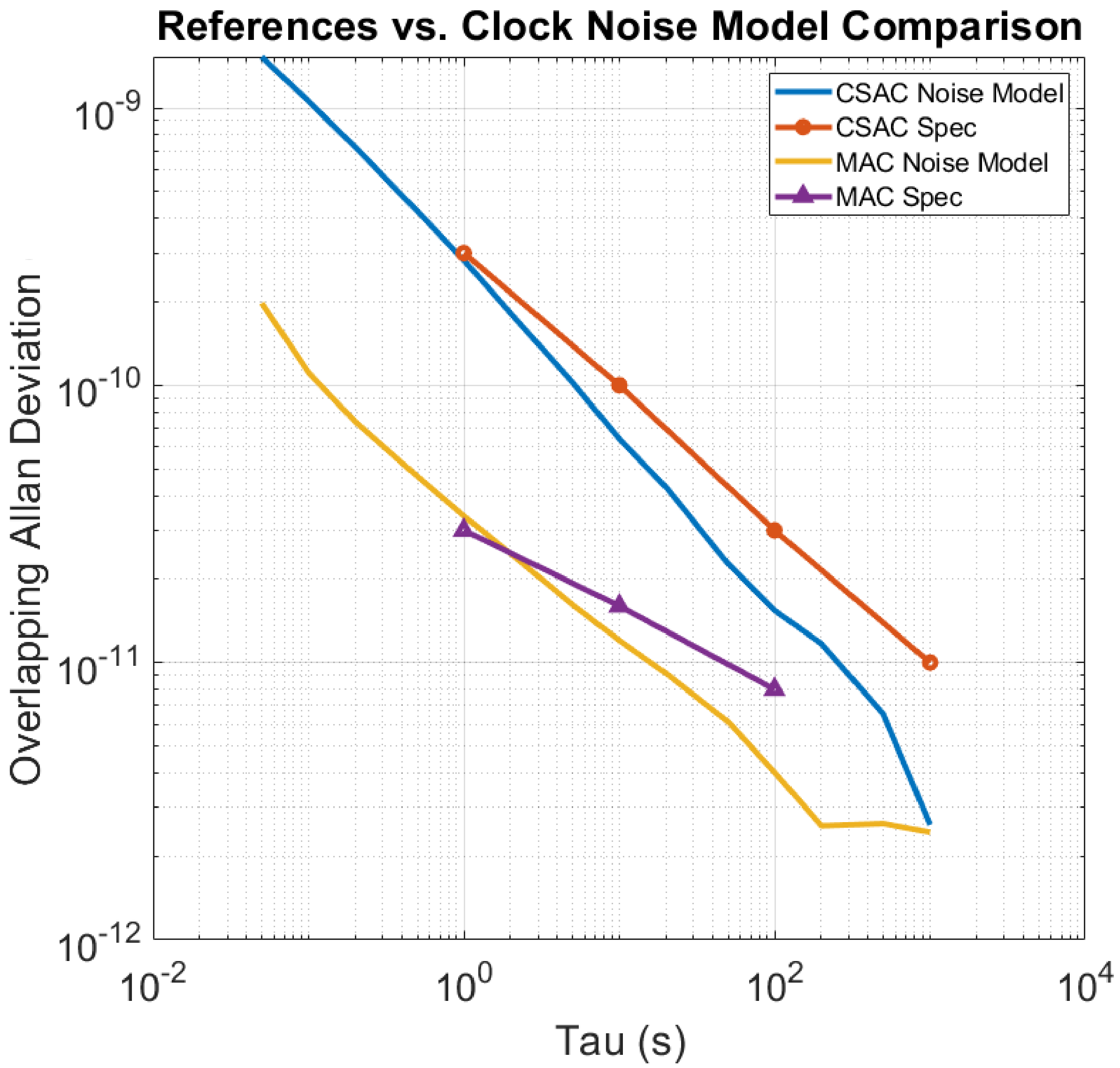
- Modeled from GPS receiver Allan deviation in Lombardi, et al. 2001
- Timing performance:
  - < 1 ns at 1 s avg. time
  - < 43 ns at ~12 hrs (43,200 s)

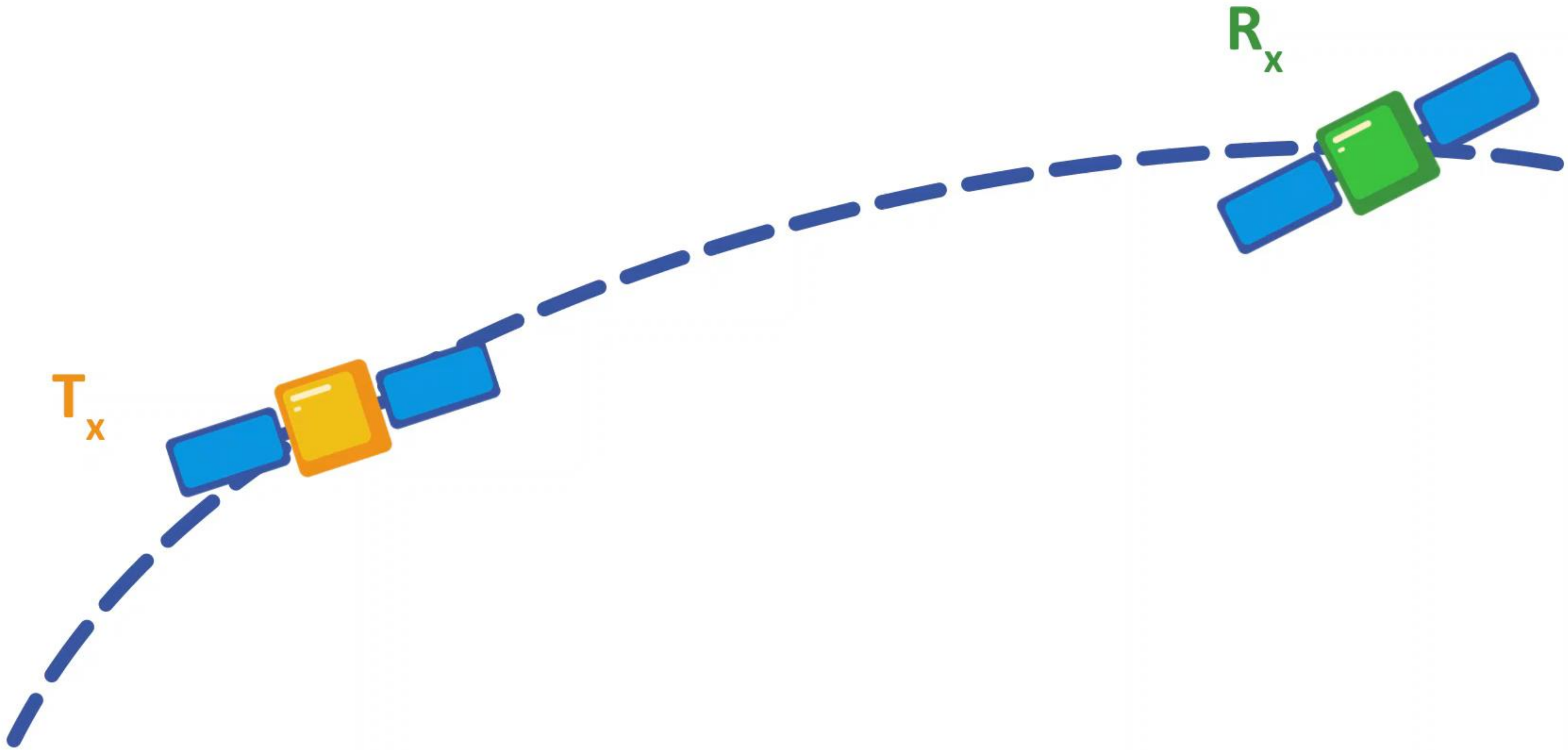


7. GPS receiver performance: Lombardi, M.A., et al., "Time and Frequency Measurements Using the Global Positioning System," *Cal Lab: The International Journal of Metrology*. 2001.

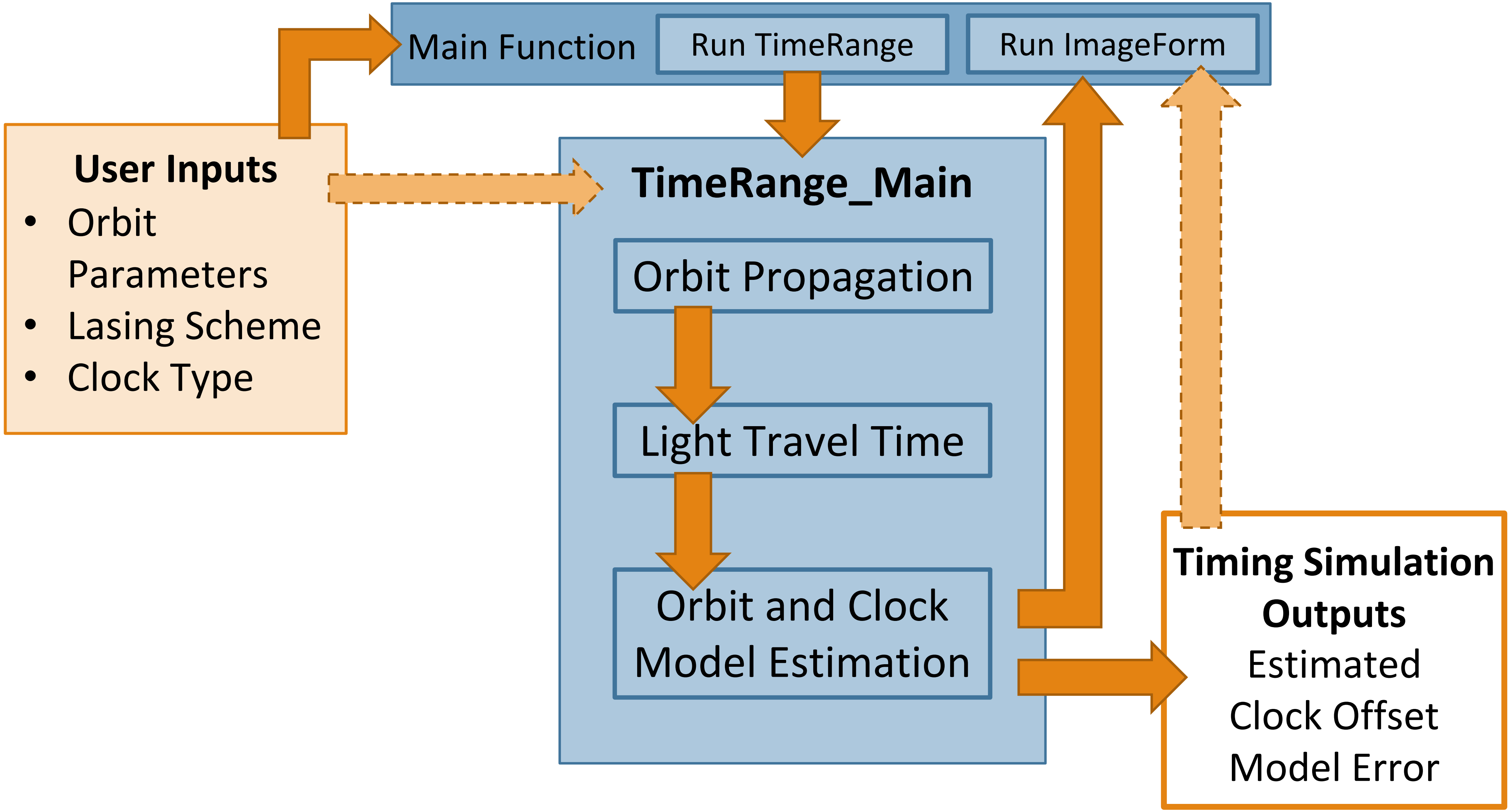
On-Board Clock Models

- On-board spacecraft clock options:
  - CSAC (cesium-based)
    - < 0.5 ns at 1 s avg. time
  - MAC (rubidium-based)
    - < 50 ps at 1 s avg. time
- Offset between independent spacecraft clocks is of interest




T_x
R_x

Timing Simulation: Overview



Timing Simulation: Estimation

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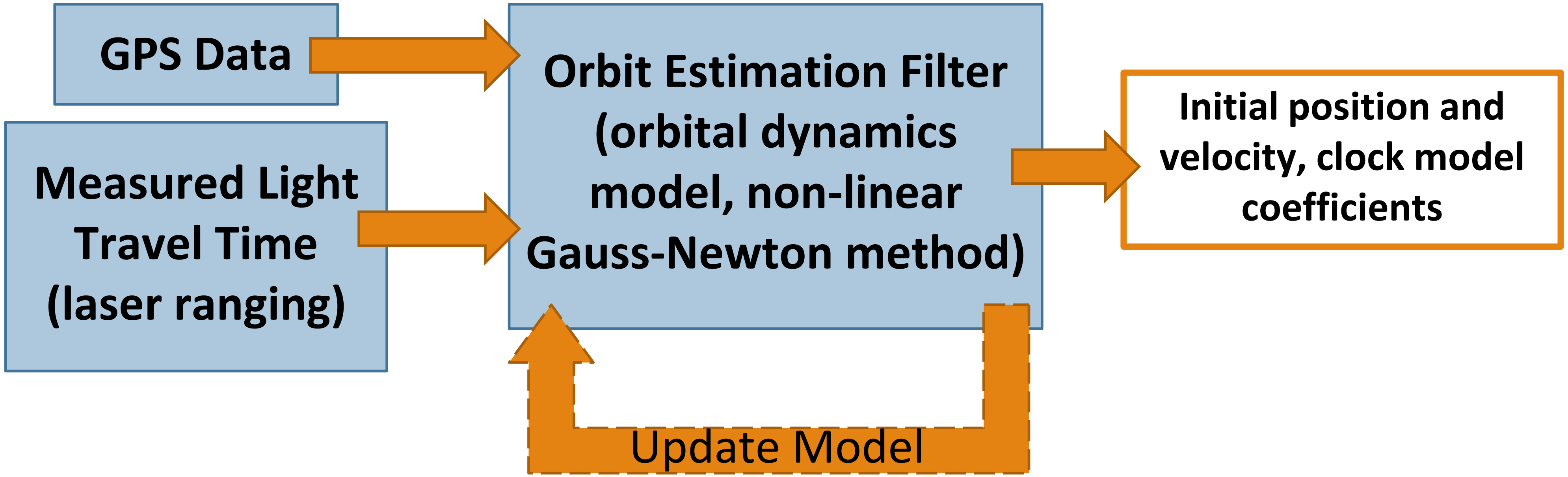
Light Travel Distance	$c\,\tau = \lvert Rtx(t) - Rrx(t+\tau)\rvert + c\,\chi(t)$
Clock Model	$\chi(t) = a2 * \Delta t^2 + a1 * \Delta t + a0$

State (X) Estimate

$$X = \begin{bmatrix} r_1 \\ v_1 \\ r_2 \\ v_2 \\ a_n \end{bmatrix}$$

clock coefficients

$$a_n = \begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix}$$

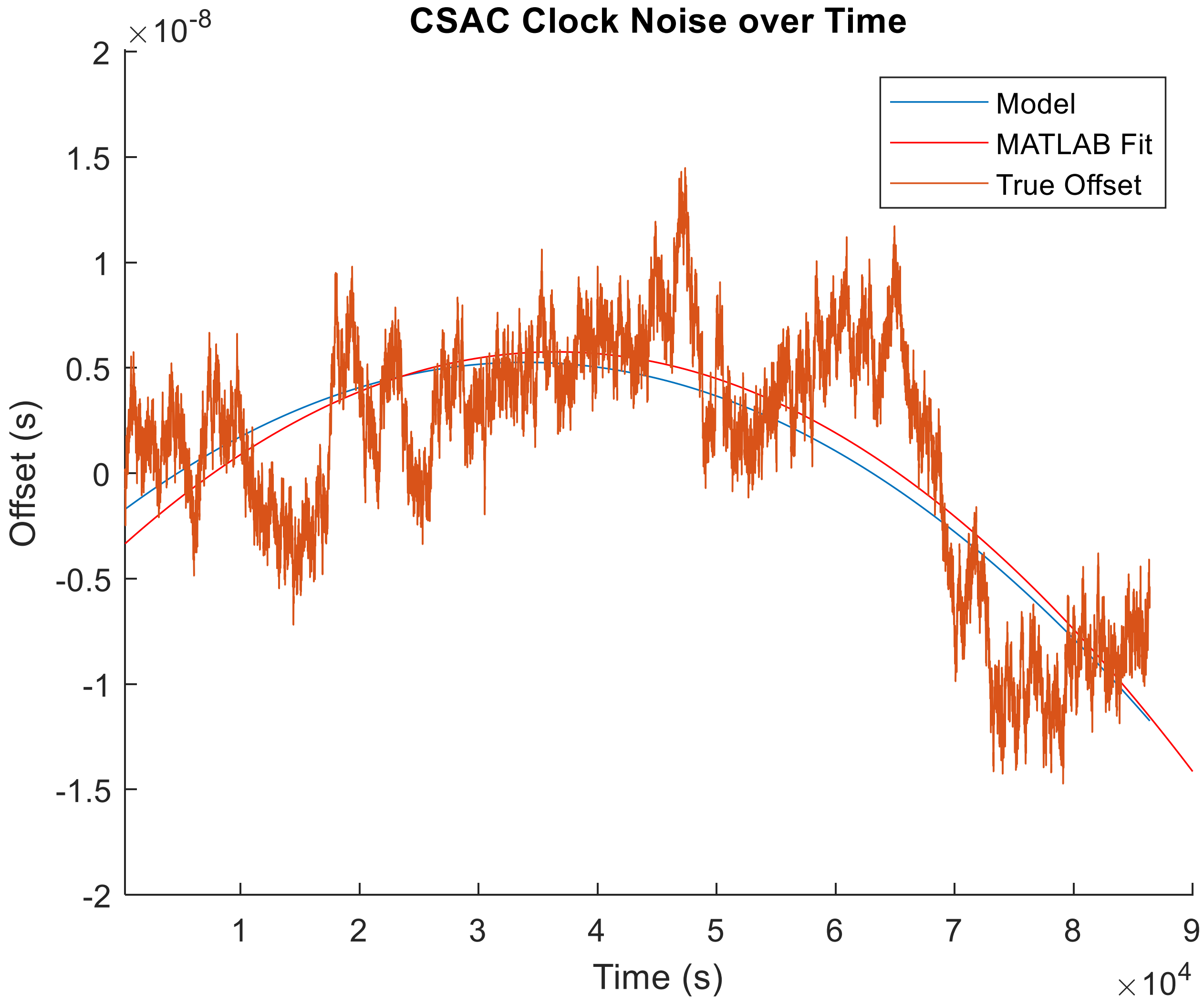


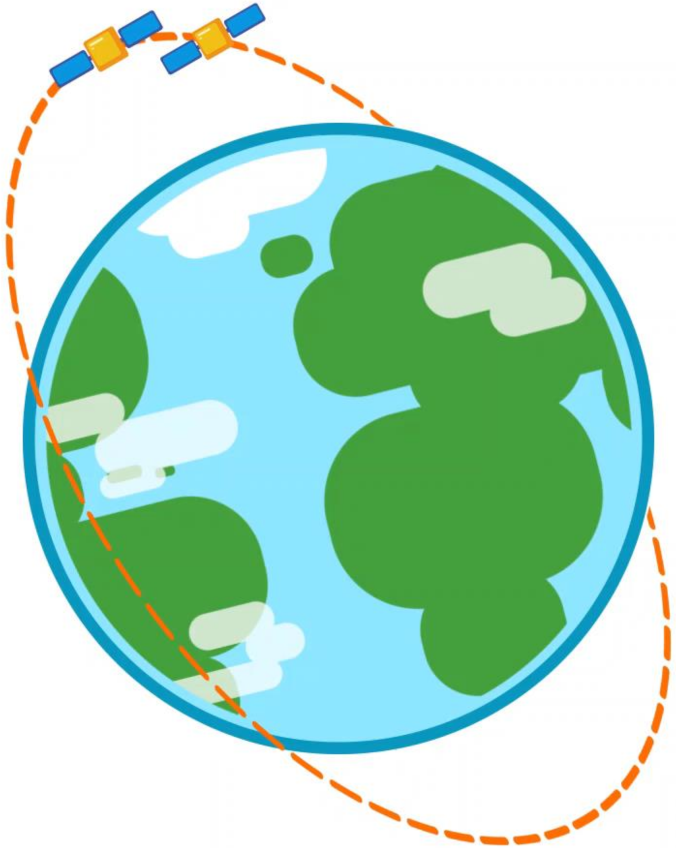
Timing Simulation: Results

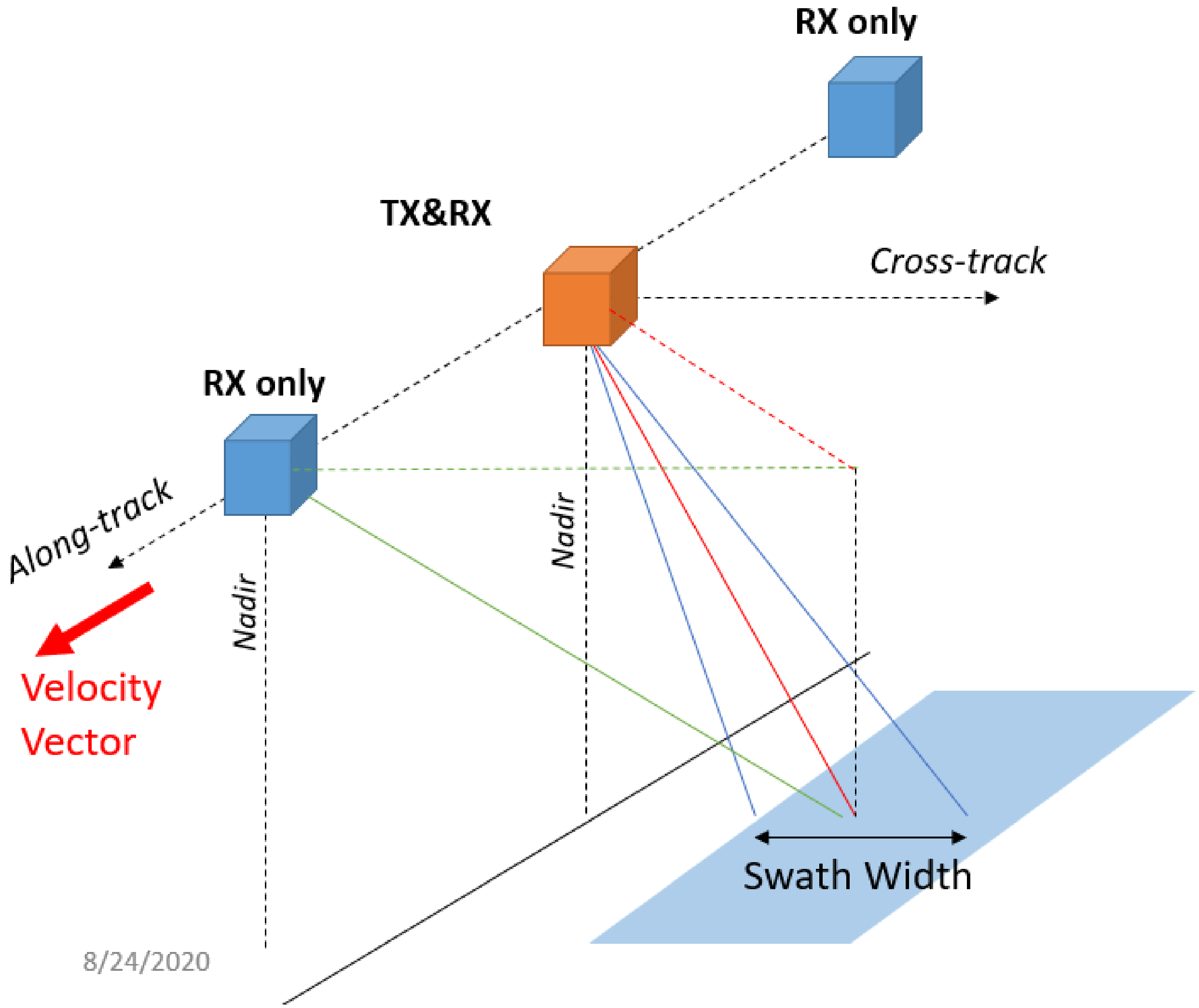
Clock error RMS: 3.7 ns

Clock Coefficient	Value (ns)
$a2$	-46 ± 1.0
$a1$	56 ± 1.1
$a0$	-12 ± 0.24

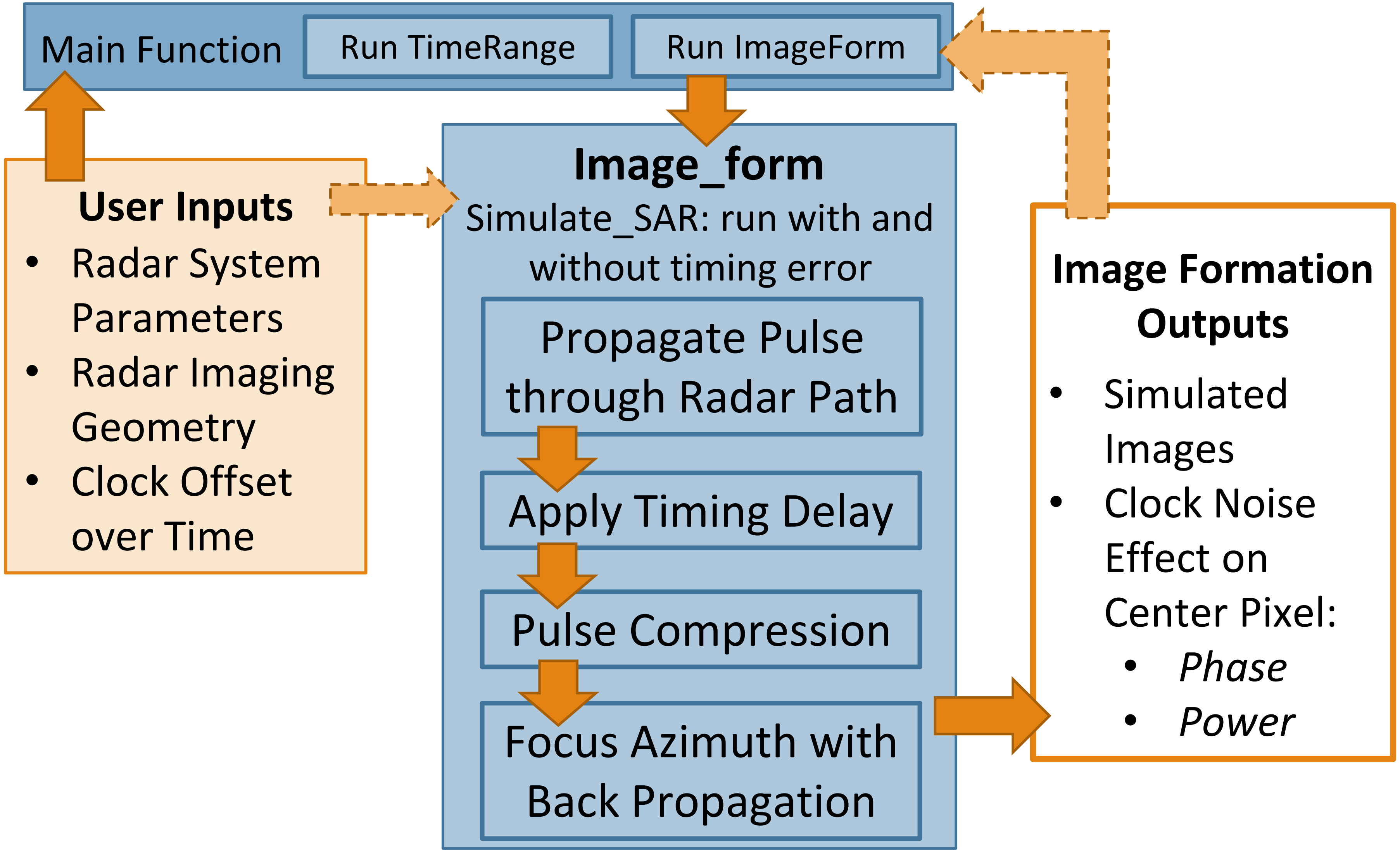
$$\chi(t) = a2 * \Delta t^2 + a1 * \Delta t + a0$$



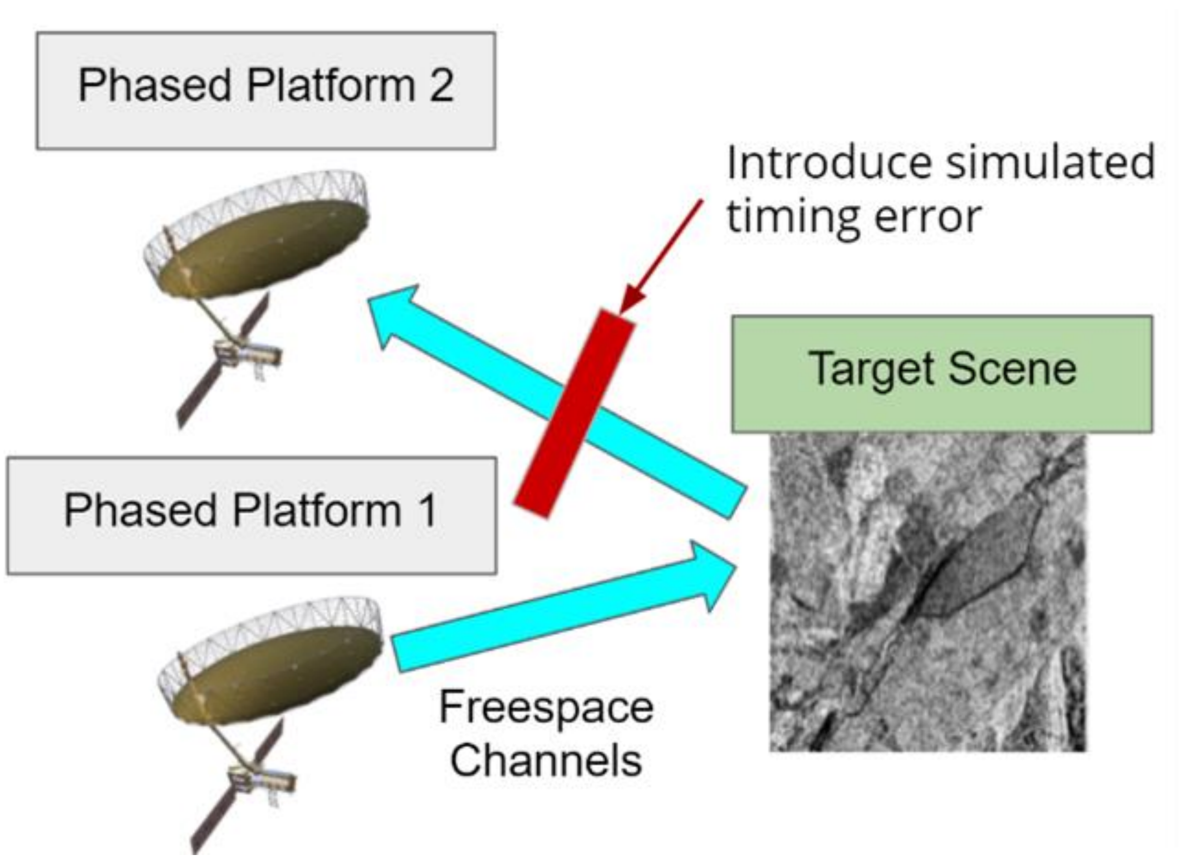


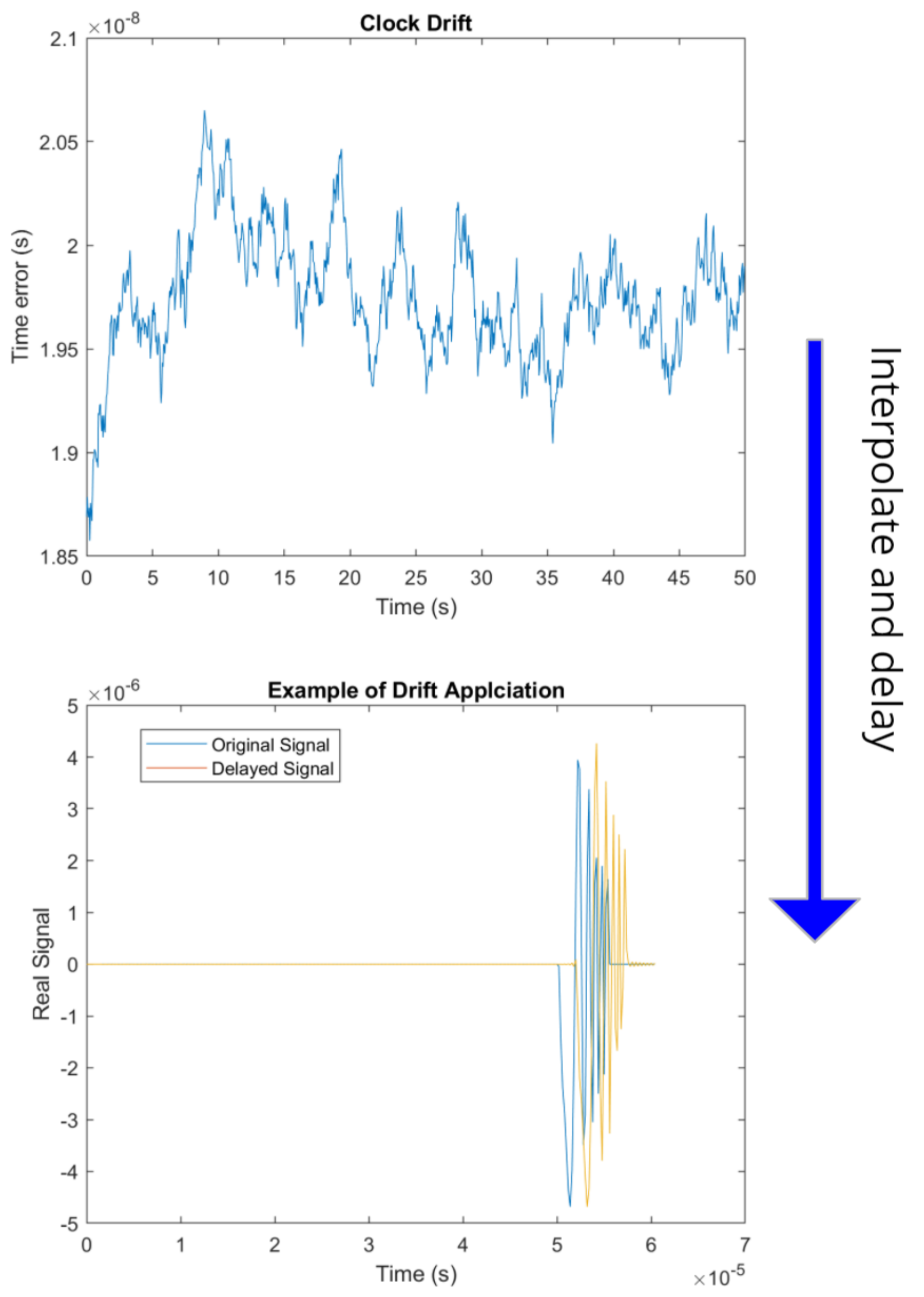

RX only
TX&RX
Cross-track
RX only
Along-track
Nadir
Nadir
Velocity
Vector
Swath Width

Radar Simulation: Overview



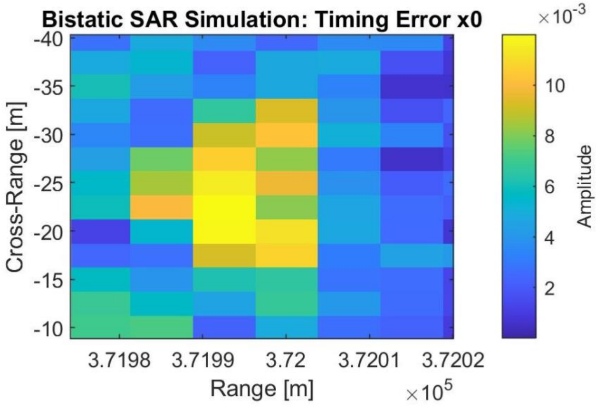
Radar Simulation: Propagation



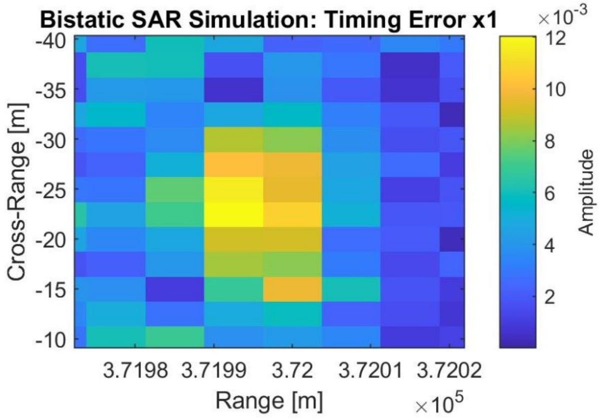


Radar Simulation: Results

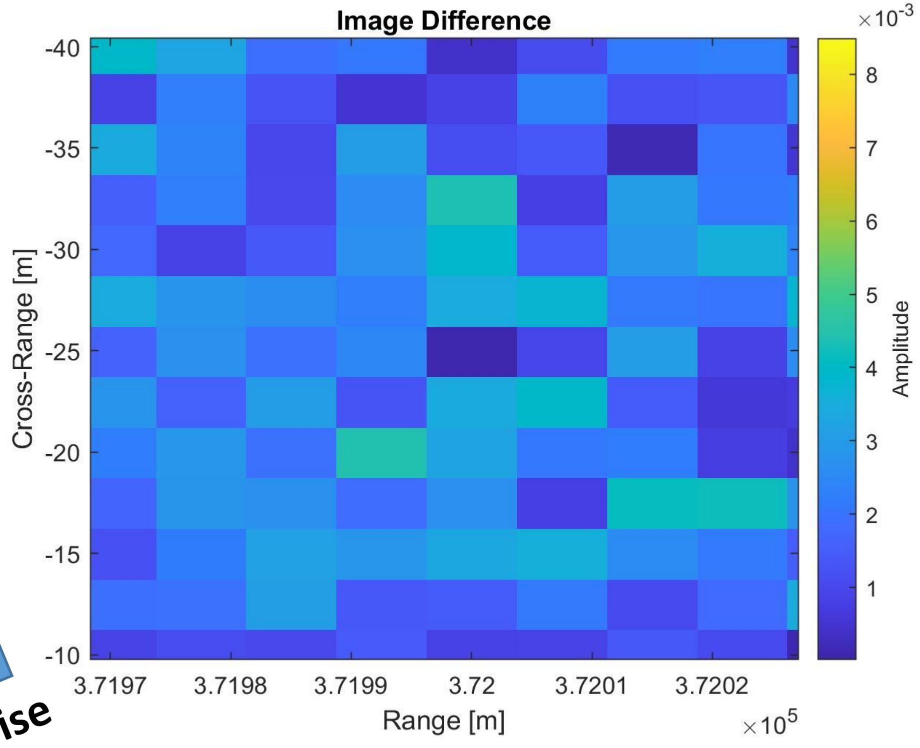
No Timing Error



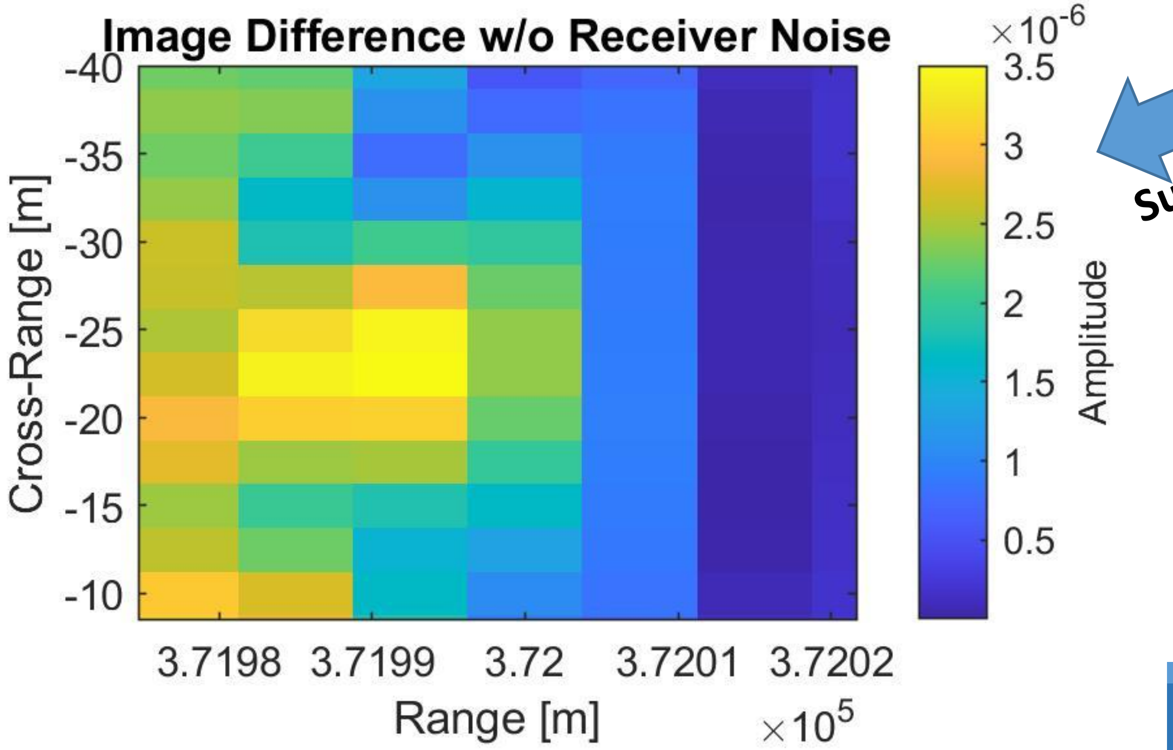
With Timing Error



Difference



Subtract Rcv Noise



Parameter	With Receiver Noise	Without Receiver Noise
Clock Error Induced Power Change	0.033 dB	-0.0003 dB
Clock Error Induced Phase Change	6.2 degrees	0.017 degrees

Summary and Conclusion

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- **Tool for evaluation:** timing error effects on orbital bistatic SAR systems
- **Case analyzed:**
  - 2 s/c in LEO, GPS position and timing measurements
  - Optical time-transfer, on-board CSACs
- **Tool use:**
  - Mission development
  - Detailed performance estimation
  - Determination of timing performance goals

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